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Calculation of dose conversion factors for doses in the fingernails to organ doses at external gamma irradiation in air

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HIGHLIGHTS

- Elemental composition and density of nails were determined.
- MIRD-type mathematical human phantom with arms and hands was created.
- Organ doses and doses to nails were calculated for external photon exposure in air.
- Effective dose and nail doses values are close for rotational and soil surface exposures.

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ABSTRACT

Absorbed doses to fingernails and organs were calculated for a set of homogenous external gamma-ray irradiation geometries in air. The doses were obtained by stochastic modeling of the ionizing particle transport (Monte Carlo method) for a mathematical human phantom with arms and hands placed loosely along the sides of the body. The resulting dose conversion factors for absorbed doses in fingernails can be used to assess the dose distribution and magnitude in practical dose reconstruction problems.

For purposes of estimating dose in a large population exposed to radiation in order to triage people for treatment of acute radiation syndrome, the calculated data for a range of energies having a width of from 0.05 to 3.5 MeV were used to convert absorbed doses in fingernails to corresponding doses in organs and the whole body as well as the effective dose. Doses were assessed based on assumed rates of radioactive fallout at different time periods following a nuclear explosion.

1. Introduction

In large-scale radiation incidents, there is a critical need to rapidly and reliably differentiate people who did or did not receive a clinically significant dose so that those with a significant dose can be triaged to receive immediate medical attention for radiation injury. A whole body dose of about 3.5 Gy has been estimated to be lethal, without medical treatment, to 50% of the population within 60 days ($LD50_{60}$). Therefore, to improve survival rates for very large populations potentially exposed in a radiation event, a reasonable threshold above which people should be triaged for medical care is generally set at a measured whole body dose of about 2 Gy (Swartz et al., 2014).

Current guidelines for methods of biodosimetry at the level of the individual are based on clinical signs and symptoms and assays based on changes in white blood cells (WBC). However, these biologically-based responses are not uniquely indicative of exposure to ionizing radiation and associated changes may not occur promptly enough to facilitate initial triage. So, especially in the early phase of a large-scale event, biodosimetry methods that are based on physical changes in the body, which occur nearly instantaneously with exposure, offer some especially useful advantages. Based on extensive research investigating the sensitivity of the physical response of nails to ionizing radiation, using electron paramagnetic resonance (EPR) spectroscopy to measure dose in fingernails and toenails has been proposed as a physically-based biodosimetry method to use in initial triage. More specifically, allowing for proper collection and storage of samples, and accounting for water content, mechanical stress and signal fading,

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EPR-based dosimetry in nails could in the foreseeable future provide a reliable dose assessment for an individual with a detection limit of the order 1–2 Gy (Reyes et al., 2008; Wilcox et al., 2010; He et al., 2014).

However, to correctly interpret the doses absorbed in nails and to measure the individual dose for purposes of treatment triage, it is also necessary to have prior knowledge of the ratio between the dose absorbed in fingernails and effective whole body or organ dose for a broad photon energy range and standard irradiation geometries. Such relations or dose conversion factors (DCF) can be calculated by Monte-Carlo methods using geometrical models of various itemization levels ranging from simple to very complex forms.

Monte-Carlo codes have previously been widely and successfully implemented for EPR-based dosimetry to relate the doses in tooth enamel or other materials of interest to effective organ-specific and whole body doses for external photon irradiation using both mathematical models (Takahashi et al., 2001) and voxel models (Ulanovsky et al., 2005). In the case of neutron irradiation, DCFs for tooth enamel were reported by Khailov et al. (2010). Herve et al. (2007) calculated the relationships between the dose to the organs and the dose to teeth, bones and non-biological samples (such as mobile phones) located in the pockets of victims' clothes, for different external exposures representative of accidental situations.

For external irradiation there is a set of well-known idealized irradiation geometries in a vacuum, which are commonly used to represent the actual conditions of exposure. Since nails are located on the top surface of the fingers, frontal irradiation of a hand with high energy photons may not create secondary electron equilibrium in nails with the result that the dose absorbed in nails could be much less than the dose in adjacent tissues. Therefore, to avoid mis-estimating the doses measured in nails, calculations have to be made in realistic conditions, in particular by taking into account the presence of air around the person exposed to radiation field.

One of the most frequently encountered scenarios in practical geometries of external irradiation is the geometry of gamma irradiation produced by fission products deposited on the ground surface. The intensity and energy spectra of the gamma radiation emitted by fission products is known to depend on time elapsed following the detonation and release of ^{235}U fission products (French, 1965).

This paper aims to provide conversion factors for absorbed doses in fingernails related to doses to various organs (listed in Table 4) and to the whole body as well as the effective dose for several homogenous external gamma-ray geometries of irradiation in air as well as the geometry where irradiation could occur from a contaminated soil surface. Using data obtained for real fallout spectra, DCF were also calculated to estimate the feasibility of using fingernails to assess the effective and absorbed whole body doses in victims during triage in an area contaminated with gamma emitting radioactive materials.

2. Methods of computation

2.1. Elemental composition and density of nails

The concentration of the radiation-induced radicals in nails obviously varies in direct proportion to the absorbed dose in nail keratin. For purposes of our investigation the elemental composition of nails (Table 1) was determined using the amino acid composition of nail keratin from Marshal (1980) as reported by Paschou (2011). Our calculations took into account nail water content of 18% relative to dry weight, according to methods reported by Venkat Rao (2010). Nail density value of 1.27 g/cm^3 was taken from Dias et al. (2007).

Table 1
Elemental composition of nails. Mass% – mass composition of each element in nail (water content – 18%) in mass %.

Element	C	O	N	H	S
Mass %	48.98	22.53	18.13	6.86	3.45

The term "absorbed doses to nails" used throughout this article refers to deposited energy per mass in finger nail volume elements filled with nail keratin (taking into account the water content of nails). The conversion from any directly measureable quantities at calibration (such as the dose in water or air kerma) to doses calculated for nails could be made using the ratios of appropriate mass energy absorption coefficients. For this purpose values of mass energy absorption coefficients (μ_{en}/ρ) for nail keratin were calculated as mass-weighted sums from the μ_{en}/ρ values for their atomic components taken from Hubbell (1982). The resulting energy dependence of μ_{en}/ρ for nails according to their elemental composition in Table 1 are presented in Table 2.

The relations of μ_{en}/ρ values for soft tissue, air and water (taken directly from Hubbell (1982)) to the calculated μ_{en}/ρ values for nails are also given in Table 2 for ten photon energies from 0.01 to 10 MeV. They are seen to be almost constant for photons with energy more than 0.1 MeV. To make a fast conversion from the doses in tissue, air and water to the doses in keratin in the photon energy interval 0.1–10 MeV the dose conversion factors were calculated as ratios of the corresponding μ_{en}/ρ values integrated over this energy interval. This dose conversion factors values for tissue, air and water were calculated to be equal to 1.04, 0.95 and 1.05, respectively.

2.2. Phantom description

To calculate the nail doses and organ doses the hermaphrodite mathematical body phantom (Fig. 1a) was created on the basis of a standard mathematical model of an adult designed by Cristy and Eckerman (1997). The standard model does not contain hands and has its arms included in the trunk. In order to adapt it for the purposes of the present study, the trunk width of the original model was reduced and two arms with hands of 2.5 kg each on both sides of the phantom were added. The distance from the middle fingertip to the ground was about 74 cm.

Leg dimensions were also adjusted to correlate with the new trunk dimension and to preserve the overall weight of leg tissue and bones of the standard phantom. Most internal organs composed of soft tissue were retained in their original positions in the trunk. Scapulars and lungs were moved towards each other (scapulars by 2 cm, lungs by 1 cm) and six upper ribs widths of the original model were slightly reduced.

The geometrical model of the hand with five nail regions was composed from a number of anatomical regions of complicated shapes (Fig. 1b). The thumb was rotated 30° clockwise with respect to the other fingers. All five nail regions had the same thickness of 0.3 mm. Nail mass varied from 24.3 to 63.9 mg.

The overall sum of the volumes and weights of the phantom parts made of soft tissue and bones remained the same within 1.5%. The sum of bone weights of arm, forearm and hand (of the created phantom) also remained equal within 3% to the weight of the arm bone of the unmodified phantom. The soft tissue, lung tissue and bone elemental composition and density were also taken from Cristy and Eckerman (1997).